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Impact of COVID-19 outbreak measures of lockdown on the Italian Carbon Footprint

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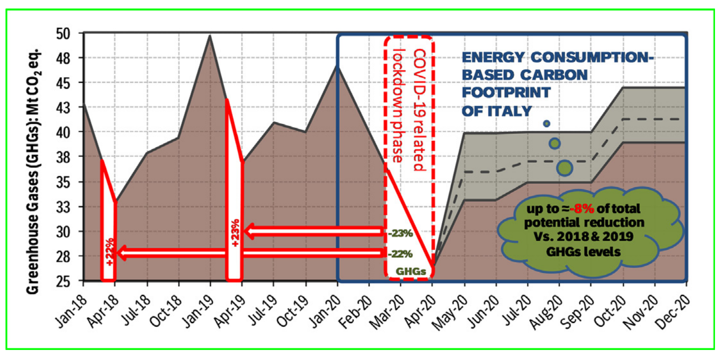
HIGHLIGHTS

- Italy has been among the most affected countries worldwide by the COVID-19 outbreak.
- Knowledge is scarce on the environmental consequences of COVID-19 related lockdown.
- A carbon footprint (CF) assessment has been applied to inform on these consequences.
- ~20% of impact has been avoided from the lockdown in Italy, compared to past years.
- If the CF depends on how the economy will upturn, Italy may save up to 45 Mt CO_2eq.

GRAPHICAL ABSTRACT



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ABSTRACT

Stringent lockdown measures implemented in Italy to mitigate the spread of COVID-19 are generating unprecedented economic impacts. However, the environmental consequences associated with the temporary shutdown and recovery of industrial and commercial activities are still not fully understood. Using the well-known carbon footprint (CF) indicator, this paper provides a comprehensive estimation of environmental effects due to the COVID-19 outbreak lockdown measures in Italy. Our aim was to quantify the CF associated with the consumption of energy by any economic activity and region in Italy during the lockdown, and then compare these environmental burdens with the CF calculated for analogous periods from 2015 to 2019 (~March and April). Complementarily, we also conducted a scenario analysis to estimate the post-lockdown CF impact in Italy. A consumption-based approach was applied according to the principles of the established Life Cycle Assessment method. The CF was therefore quantified as a sum of direct and indirect greenhouse gases (GHGs) released from domestically produced and imported energy metabolism flows, excluding the exports. Our findings indicate that the CF in the lockdown period is ~—20% lower than the mean CF calculated for the past. This means avoided GHGs in between ~5.6 and ~10.6 Mt CO_2e. Results further suggest that a tendency occurs towards higher impact savings in the Northern regions, on average ~230 kt CO_2e of GHGs avoided by province (against ~110–130 kt CO_2e in central and Southern provinces). Not surprisingly, these are the utmost industrialized areas of Italy and have been the ones mostly affected by the outbreak. Despite our CF estimates are not free of uncertainties, our research offers quantitative insights to start understanding the magnitude generated by such an exceptional lockdown event in Italy on climate change, and to complement current scientific efforts investigating the relationships between air pollution and the spread of COVID-19.

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1. Introduction

Coronavirus disease 2019 (COVID-19) is an infectious disease caused by *severe acute respiratory syndrome coronavirus 2* (Zhu et al., 2020). It was first reported in a small cluster in Wuhan, Hubei Province, China, on December 2019 (Lu et al., 2020; Huang et al., 2020), and subsequently spread all over the world (Acter et al., 2020). Starting from the end of February 2020, contagious of COVID-19 has spread in Italy, especially in the Northern area. At the beginning of March 2020, the World Health Organization has declared COVID-19 as a public health emergency of international concern (WHO, 2020) mainly due to its high contagiousness and aggressive course. Italy has been the first country in Europe to put in place a nationwide lockdown to protect the population health, through the implementation of a stringent confinement approach. Such a lockdown, imposed from Italian Government on March 9th, has put in place a number of economic policies, legal constraints and social rules and measures to limit as much as possible the movement of Italian citizens and their physical contact, thus making the whole country a protected zone (Zanin et al., 2020). As such, around 60 million of people in Italy have currently experienced an unprecedented phase of lifestyle changes due to the outbreak of COVID-19 (Burgio et al., 2020). As a consequence of these restrictions, most of the economic activities in Italy have stopped from one day to another, dramatically impacting on the national production and consumption processes.

The lockdown in Italy has also halted for more than one month the most impactful - for both ecosystems and human health - activities of production and consumption of energy and materials (such as transport and industrial manufacturing). The effects of these changes have been investigated in several recent studies that observe a meaningful impact mitigation of the atmospheric pollution associated with reduced anthropogenic activities during the COVID-19 outbreak in Italy (Fattorini and Regoli, 2020; Carugno et al., 2020; Contini and Costabile, 2020). The reduction in such air pollution concentrations is also showed in a video produced by the European Space Agency using data gathered by the agency's Copernicus Sentinel-5P satellite (ESA, 2020). As before the lockdown, Northern Italy was one of the most polluted area in Europe. Some studies have therefore focused on analyzing the retroactive effect that pollution may have played on the lethality rate of the virus (Ogen, 2020; Conticini et al., 2020) and its spread (Sciomer et al., 2020; Setti et al., 2020). However, analyses investigating the proactive effect of lockdown on the environment are quite scarce and focus on air pollution in China (Bao and Zhang, 2020). While the negative repercussions of the lockdown in Italy on the society and economic productivity of the country are evident (Lucchese and Pianta, 2020), it is reasonable to hypothesize that tangible benefits for the environment have instead been generated (Muhammad et al., 2020). In particular, the lockdown related provisional closure and slow recovery of most of the economic activities in Italy is expected to have an impact on short-term greenhouse gas (GHG) emissions released in atmosphere (Helm, 2020). For instance, a preliminary study estimated that lockdown in China has temporarily reduced GHG emissions by a quarter (CarbonBrief, 2020). Unlike atmospheric pollutants (Collevignarelli et al., 2020), GHG reductions are difficult to be revealed via satellite imagery due to their long-term storage in atmosphere (IPCC, 2005). Therefore, supplementary analyses based on the carbon footprint (CF) estimation, which is based on the GHGs inventory, are urgently needed to provide such a relevant information (Caro, 2018).

Lockdown in Italy has mainly concerned industries, commercial and transportation activities, which are strictly connected with the consumption of energy and their associated GHG emissions. According to the Italian GHG inventory submitted to the Climate Change secretariat of United Nations, in 2017, the energy sector in Italy has contributed to around 80% of the total country GHG emissions (UNFCCC, 2020). This account mainly includes GHG emissions from energy used by industries and transport (which contribute with ~45% and ~29% of GHG emissions, respectively, to the total emissions from the energy sector), but also by other sectors (~24%) (UNFCCC, 2020). In the light of the lockdown imposed at the beginning of March 2020 most of the activities belonging to the energy sector in Italy have been shut down, with potentially huge effects on the associated CF. Understanding the causes and the effects of these potential impacts may be crucial to provide additional knowledge in support of the upturn of the Italian economic engine while reducing the negative repercussions on climate change (Zambrano-Monserrate et al., 2020). Assessing the CF mitigation opportunities originated from this exceptional lockdown event may reveal important insights on how to accomplish the current Italian climate targets and put a concrete basis on the effort required to reach them.

The national production of energy and its final demand, which also incorporates the CF associated with imported energy commodities, are responsible for the majority of GHG emissions due to the country activities (since energy is consumed in every branch of the economy). Starting from such a consideration, the aim of this paper was to estimate the impact on the reduction of CF potentially generated during and after the lockdown, by accounting for the GHGs emissions associated with the decrease in energy consumptions by each economic sector and area of province in Italy. While the lockdown contextual impacts are compared with the historical trends of GHG impacts calculated on a monthly basis for the timeframe 2015 to 2019, to assess the post-lockdown related CF a scenario-based analysis was performed, defining three possible scenarios of CF potentially occurring as a consequence of the variation of the Italian Gross Domestic Product (GDP).

Estimating and comparing the CF trends over time, space, energy consumption typology and economic sector in Italy allowed to raise some relevant questions of interest for both the scientific community and decision-makers, such as: how many GHG emissions have been saved in Italy during the lockdown?; what are the sectors that have reduced/increased their GHG emissions more?; which Italian regions have been affected more?. By addressing these questions, the results of this paper provide a timely background knowledge to possibly support long-term decisional processes in the field of climate change adaptation and mitigation strategies.

2. Materials and methods

2.1. Case study

Italy is a Southern European country with a territorial extension of ~301′338 km^2 and a high population density (more than 60 million people in total, with ~200 inhabitants/km^2). According to the recent year 2018's statistics (ISTAT, 2020a; see Fig. 1), the spatial distribution of the resident population is quite heterogeneous across the 107 administrative country divisions being either a province or a metropolitan city (hereafter *Provinces*, for simplicity), which are grouped into 20 *regions*: around 46% of the total population is concentrated in the Northern regions (*Piemonte*, *Valle d'Aosta*, *Lombardia*, *Trentino Alto Adige*, *Veneto*, *Friuli Venezia Giulia*, *Liguria* and *Emilia Romagna*), around 20% in the four central regions (*Toscana*, *Umbria*, *Marche* and *Lazio*), the ~36% of which in the province of Rome, and the remaining ~34% in the Southern Italy ("Mezzogiorno"), which comprises the regions of *Abruzzo*, *Basilicata*, *Calabria*, *Campania*, *Molise* and *Puglia*, and the islands (*Sicilia* and *Sardegna*).

As also shown in Fig. 1, the economic productivity of the country (in terms of gross domestic product, GDP), has been smoothly increasing over time since 1990, with some periods of stagnation, decreases and low growth rates in the latest 20 years following in particular the global economic crisis of 2008 and the recession years of 2012 and 2013. The slight GDP upturn observed since 2015 has been now drastically interrupted with the occurrence of the COVID-19 outbreak related lockdown measures. These started at the end of February 2020 for some "red" province and municipality areas (according to the D.L. 23/02/2020 No.6), and covering the entire country for around two months

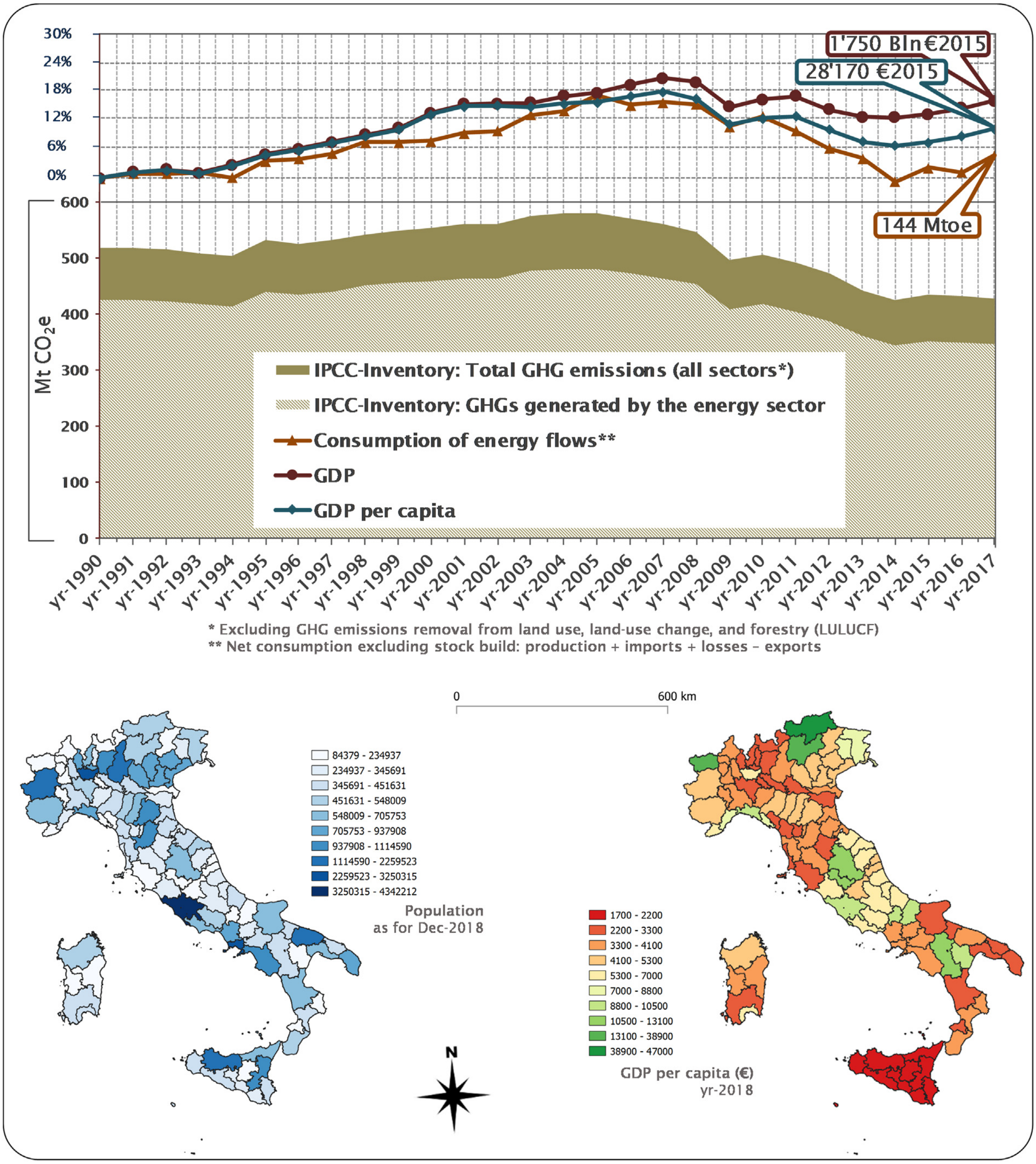

Fig. 1. Context of the case study. Top: i) historical trend of greenhouse gas (GHG) emissions in Mt CO_2e (both total and generated by the energy sector, the latter being ~80% of the total over time; source: IPCC GHG emissions inventory methodology; see UNFCCC, 2020); ii) historical trends of the total gross domestic product (GDP) and GDP per capita normalised to the year 1990 and profiled using values at constant price, euro 2015 (source: WBG, 2020); iii) historical trend of energy consumptions normalised to the year 1990 (source: Eurostat, 2020). Bottom: i) distribution of resident population (60.4 million in total); ii) distribution of GDP per capita in 2018 across the 107 Italian province areas (source: ISTAT, 2020a).

starting from the 10th of March 2020 (D.P.C.M. 11/03/20) until the smooth re-opening of all the economic activities between the 4th May 2020 and the 17th and 24th of May 2020 (D.P.C.M. 26/04/20). In total, more than one hundreds among laws, normative acts and policies were exceptionally adopted by the Italian government for and during the lockdown phase (GU, 2020), which counted approximately two months as it was considered in this paper: "March & April 2020". As discussed later in Section 4.3, selecting these two months as a reference lockdown period for the CF assessment model allowed more consistency in the GHGs accounts, since most of the data were provided on a monthly basis.

Understanding the environmental consequences (in terms of carbon footprint) of such a lockdown was the scope of this work. Historical trends of the Italian carbon dioxide equivalent emissions (hereafter "CO_2e") such as CO_2, CH_4 and NO_2, which represent the most common greenhouse gases (GHGs), are estimated on annual basis by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006). According to the latest GHGs inventory protocol implemented by the IPCC, GHGs release trends follow the GDP growth rate until the end of the '90s, after which the amount of emissions starts to lowering because of the larger use of renewable resources and energy solutions (Fig. 1). Most of GHGs release is allocated to the energy sector, which historically contributes to around 80% of the total CO_2e emitted. The pattern of energy consumption flows, which include solid fossil fuels, manufactured gases, oil and petroleum products, natural gas, renewables and biofuels, non-renewable waste, heat and electricity (see next section), inherently follows the GHGs emissions trend. Then, it diversifies from the GDP in the latest years most likely because of the introduction of more clean technologies and the use of renewable resources. Not surprisingly, the domestic production share of renewables and biofuels has increased by ~25% in 1990 up to around 45% in 2005, and then again up to more than 70% in the latest 2016–2018 (Eurostat, 2020), which can partially explain the decreasing GHGs patterns observed in this timeframe (Fig. 1).

2.2. Methodology

2.2.1. Energy consumption accounts

The analysis conducted in this paper first focused on building a complete inventory of the energy flows consumed in Italy before the lockdown (monthly consumptions from January 2015 to February 2020) and during the lockdown (March and April 2020). A consumption-based approach (whereby *Consumption* = *Production* + *Imports* – *Exports*) as previously proposed in Caro et al. (2015) was adopted to calculate the net energy flows used up by the resident population and the industrial, agricultural, and tertiary sector activities. This approach is based on the compilation of a detailed inventory of the life cycle activities directly and indirectly needed to produce the energy flows eventually consumed by those sectors, following the Life Cycle Assessment (LCA) methodology (Hauschild et al., 2018). The scope and system boundary of the analysis is depicted in Fig. 2, which shows the typical size of the Italian energy metabolism. All types of energy flow available for transformation (i.e. solid fuels and manufactured gases, oil and petroleum products, natural gas, renewables and biofuels, non-renewable waste, heat and electricity), domestically produced and/or imported, transformed, and partially lost. Exports (included in the red box with dashed line in Fig. 2) were excluded from the energy account in accordance with the abovementioned consumption-based approach. All those flows eventually consumed by the different energy and non-energy economic sectors in Italy were accounted for and converted into kilo-tonnes of equivalent-carbon dioxide according to the IPCC Global Warming Potential methodology (IPCC, 2013); see Section 2.2.2. Additionally, a time-series spatial analysis was performed to distribute this total impact across the Italian regions and provinces, as well as over time, starting from 2015 and comparing the effect of the lockdown restrictions on the accounting of energy flows and related impacts.

2.2.2. Calculation of the carbon footprint (CF)

A carbon footprint (CF) analysis was performed according to the ISO 14067:2018 standard on Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. Since the ISO 14067 refers to the LCA methodological criteria for the quantification of the CF impact indicator, each energetic flow of national consumption was multiplied by the CF value estimated for each corresponding type of unit process from the ecoinvent v3.6 life cycle database (ecoinvent, 2020). Those CF factors, reported in mass of equivalent CO_2 per reference unit of energy resource, were calculated starting from the sum of GHGs emitted in the cradle-to-gate life cycle of each resource modelled by ecoinvent (fuels, heat, electricity, raw materials, etc.; see Section 2.2.1). These GHGs were then converted into CO_2-equivalents using IPCC global warming potentials from the "IPCC 2013 GWP 100a V1.03" method (implemented in the SimaPro software, PRé, 2020). All the calculated CFs and a comprehensive description of the reference datasets from the selected ecoinvent unit processes are reported in Table S1 of the Supplementary material (SM).

To avoid double counting of GHG emissions, the original ecoinvent datasets were manipulated at the level of combustion process to exclude all the GHG emissions not directly generated by the investigated fuel. For example, the GHGs associated with the life cycle of gasoline were represented by the sum of the GHGs generated during the upstream phases of the fuel life cycle (phases from cradle to selling gate, e.g. at service station) and the GHGs generated by the downstream combustion process. Therefore, the process "*Transport, passenger car, medium size, petrol, EURO 5 {RER}| transport, passenger car, medium size, petrol, EURO 5*", which does include not only the input flow "*Petrol, low-sulfur {Europe without Switzerland}*", but also several other inputs describing the manufacture and use of the car, was modified to exclude the GHG emissions associated with these latter. The same approach was applied to the other combustion fuels, which represent the majority of energy consumption flows accounted for (see Table S1 in the SM).

2.2.3. Data availability, compilation and assumptions

2.2.3.1. Approach for data disaggregation. As reported in Table S2-SM, complete coverage of energy consumptions data before the "lockdown" period, i.e. monthly consumptions by economic sector from January 2015 until February 2020, was available for natural gas, oil and petroleum products, and electricity consumptions. For these latter, in particular, data are typically disclosed on a daily basis (Terna, 2020; Table S3-SM) and provided by energy source, geographical origin of the imports and domestic consumptions (by sector for the years 2015–2018, as well as by province). Similarly, no distribution by sector (nor by region or province) was available for oil and petroleum products in 2019 and 2020. While for solid fossil fuels and manufactured gases, data was available until January 2020, disaggregated by economic (industrial) sector. In contrast, data regarding the monthly consumption of renewables and biofuels, non-renewable waste and heat was not available (only their total amount consumed in the years 2015–2018 was accessible through the Eurostat energy balance database) (Eurostat, 2020).

Some assumptions were therefore adopted to cover the gap in monthly data consumptions for electricity all along 2019 and the beginning of 2020 (January and February), as well as for the previous timeframe 2015–2018 concerning renewables and biofuels, non-renewable waste and heat. In particular, for renewables and biofuels, non-renewable waste and heat a disaggregation of the total annual consumptions over each month (between 2015 and 2018) was performed according to the share of equivalent (in usage functions) non-renewable energy fuels for which monthly data was instead available. More specifically, solar and geo-thermal energy (with exclusion of the portion dedicated to produce electricity), primary solid biofuels, charcoal, biogases and ambient heat (i.e. use of heat pumps), which are mainly exploited by the tertiary and housing sectors (for around than 90%, 70%, 90%, 80%, 55% and 95%, respectively, between 2015 and 2018 according to Eurostat statistics; Eurostat, 2020), were adapted to follow the monthly consumption distribution of natural gas in those sectors (where around 70% of this fuel is used over the same timeframe). Similarly, the monthly distribution of blended biogasoline and blended biodiesels followed the trends of conventional motor gasoline and diesel consumptions, respectively; finally, the distribution of consumptions of heat and industrial waste (non-renewable), which mainly belong to activities from the industry, followed accordingly the one of solid fossil fuels (i.e. coal products) in the industrial sectors. Regarding the distribution of electricity by sector in 2019 and 2020, the average monthly share from the previous 2015–2018 timeframe was used.

To estimate the GHG emissions burden occurring during the lockdown period (~March and April 2020; see Section 2.1), complete datasets were available only for the electricity consumptions, and oil and petroleum products, and partially for natural gas (consumption data available only for the month of March 2020). Therefore, GHGs trends for the other energy flows (solid fossil fuels, renewables and biofuels, and non-renewable waste and heat) were estimated assuming the same consumption reduction rate observed for electricity, natural

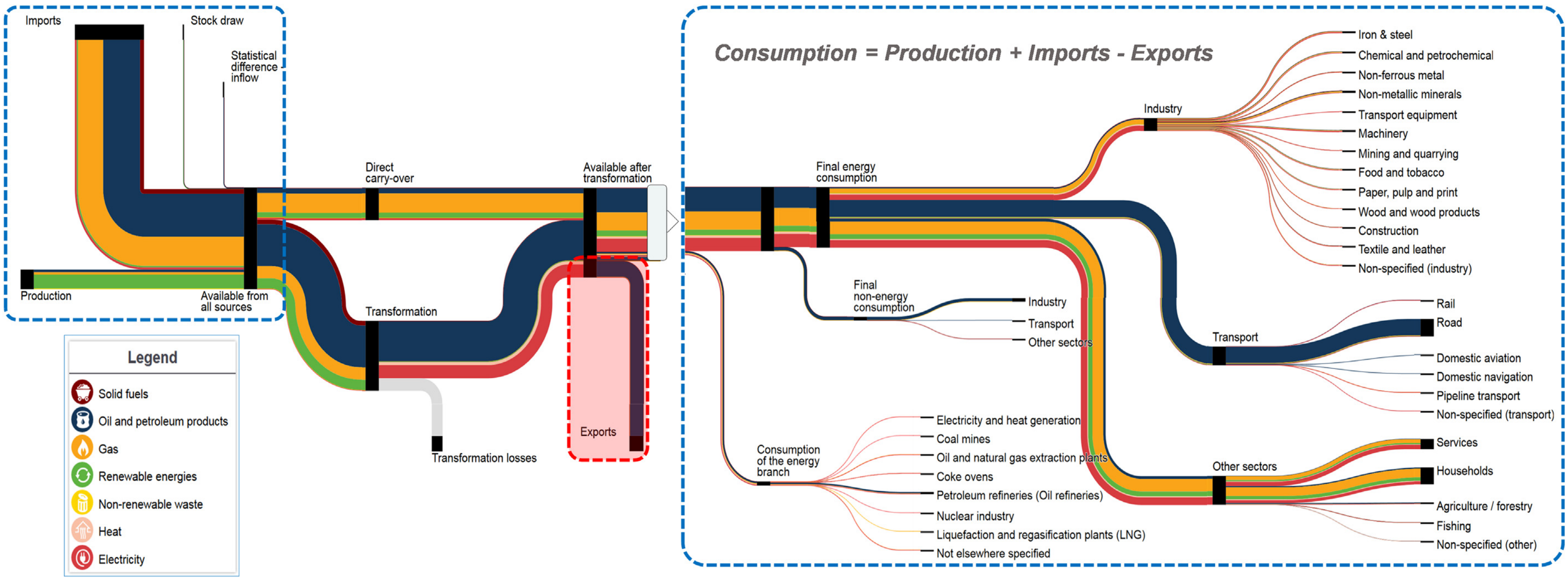

Fig. 2. Scope and system boundary of the analysis. The chart has been elaborated using Eurostat energy balance flows for Italy (Eurostat, 2020) over the historical timeframe 2015–2018 (temporal reference for data in this chart: 2018; note that the Sankey diagram for former years 2015, 2016 and 2017, is graphically very similar to the one of 2018); to be noticed that this chart does not visually include some marginal consumptions, such as for fuels to marine bunkers, stock build, international aviation and those lost in distribution and transmission, i.e. altogether, they represent less than 10% of the energy flows, that enter the final consumptions pathways, measured in kilo-tonnes of oil equivalent (ktoe).

gas and oil and petroleum products in the months of March 2019 and April 2019. More details about the specific rates calculated and applied to estimate the missing data belonging to the lockdown period can be found in Table S2.

Regarding the spatial distribution of energy consumption flows, data was collected, elaborated and presented at the scale of province (third administrative territorial level in Italy; Nation > Region > Province > Municipality). Actually, this type of geographical resolution was available only for electricity and natural gas consumptions for the historical time series 2015–2018. Therefore, to disaggregate the energy consumptions from the first to the third hierarchical level a basic allocation assumption was performed concerning the other energy flow categories, as well as to estimate the consumptions distribution over the years 2019 and 2020. Since the consumptions data of electricity and natural gas were originally broken down by economic activity in each province, the average 2015–2018 share of each sectorial consumption across the 107 provinces was used in order to allocate the consumptions over the years 2019 and 2020. In parallel, a correspondence between the economic sectors of all the subcategories of energy was performed following the NACE Rev.2 classification system and aggregating the flows into 22 economic sectors belonging to 4 macro-categories of economic activity (Industrial, Tertiary, Housing and Agriculture sectors; see Table S4-SM for further details on the classification list). In parallel, for oil and petroleum products, solid fossil fuels, non-renewable waste and heat, and solid biomass products and biofuels, the consumptions per each economic sector was redistributed across the 107 provinces using the same shares adopted for electricity and natural gas. Despite still embedding some uncertainty, applying this allocation approach (instead of an alternative based on a population density, for example) allowed to capture information about the economic activities outside the household consumptions sector. For example, a province moderately populated but with high energy consumptive activities (such as a metallurgical production plant) realistically resulted in higher amounts of allocated energy consumption flows than a province without this type of activities in its territory.

2.2.3.2. Approach for missing data estimation and definition of predictive scenarios. On top of the above data disaggregation process (by month, sector and geographical location), some assumptions were also adopted to cover the data gaps for solid fossil fuels and manufactured gases (concerning Jan-2020 and Feb-2020) as well as for renewables and biofuels, non-renewable waste and heat (concerning the latest fourteen months before the lockdown, between Jan-2019 and Feb-2020). To this end, a forecast function implemented in *Microsoft Excel* to predict values based on historical trends was used (see values in Table S2-SM), which builds upon the Holt-Winter's triple exponential smoothing approach (Brockwell and Davis, 2016). Adopting such a function was considered an effective, transparent and replicable solution to predict missing values in the present work, because of the capability of this algorithm to handle existing time series data trends with a seasonal component (which was the case of the datasets used in this study).

A final step of the analysis was to estimate the CF evolution after the lockdown period. Accordingly, three possible scenarios of CF trends were framed assuming that the impact will be directly associated with the expected upturn of the economic productivity in the next future. To this end, the CF intensity of the *added value* per each branch of activity in Italy was calculated using the disaggregated figures provided by the national institute of statistics in Italy (ISTAT, 2020a), further re-aggregated on the economic sectorial breakdown of Table S4-SM, and the CF results obtained for the timeframe 2015–2019. Data on the added value were chosen since this corresponds to the difference between the total economic output and the value of intermediary costs, and can therefore allow to estimate the growth of the economic system in terms of new goods and services available for final use, disaggregated per branch of activity. Within the historical timeframe 2015–2019, the added value in Italy constantly matches up the 90% of the GDP. Hence, this ratio, which was assumed to not ideally change in 2020, was used to estimate the GHGs associated with the GDP projected by various sources. Accordingly, the following three scenarios based on GDP forecasts were defined and then the associated CF calculated as 90% of the GDP (using the added value's CF impact shares):

1. Business-as-Usual (BaU) scenario: in this scenario, GHGs emissions were associated with an increase in economic activities as high as the increase in GDP if COVID-19 outbreak (and consequent lockdown) was not occurring. Accordingly, an increase in GDP of +1.3% compared to the last year 2019 was estimated using the Holt-Winter's forecast function introduced above. Despite it is unlikely that such an economic upturn will happen, since at March 2020 the chained volume measure of GDP already decreased by 4.7% with respect to the previous quarter (ISTAT, 2020b), such a baseline scenario is used to estimate the highest bound of the CF impact that might be possibly attained.
2. Optimistic scenario: it follows a rate of decrease in the GDP equal to −4.7% for the first quarter of 2020, with respect to the previous quarter of Oct-Dec 2019, whereby the carry-over for 2020 is −4.9%. This possibly represents the most realistic scenario.
3. Pessimistic scenario: it follows a rate of decrease in the GDP equal to −9.1% as estimated for the whole year 2020 by the latest International Monetary Fund growth projections on the real GDP (IMF, 2020).

It is worth noticing that in both the three scenarios the evolution of the GDP from the end of March 2020 until the end of December 2020 was estimated to run smoothly in order to keep a reasonable balance between the value of the GDP in the first quarter of 2020 (i.e. −4.7% as estimated by the ISTAT) and the value of the GDP at the fourth quarter, which was estimated independently for the whole year. This assumption must be considered as a methodological artefact to avoid predicting an upturn of the trimestral GDPs (at the levels of upturn predicted for the total GDP at the end of the year) already from the second quarter, which is inherently improbable. Therefore, an artificial rebalance of the "−4.7% factor" over time was applied recursively to the trimestral GDPs estimated as an equally allocated portion of the remaining GDP, i.e. $GDP_i = (annual\ GDP^{2020} - GDP^{1st\text{-}quarter\ 2020}) / 3$, with i representing the 2nd, 3rd and 4th remaining quarters of 2020. More specifically, a factor of −4.7% was artificially applied to the 2nd quarter-GDP; a factor of +2.35% to the 3rd quarter-GDP, and a factor of +2.35% to the 4th quarter-GDP.

3. Results

3.1. Carbon footprint in the lockdown period

The main finding of the present study is that the carbon footprint (CF) due to the energy consumptions occurring in Italy during the COVID-19 related lockdown (hereafter referred to the months of March and April 2020, for the sake of simplicity) is substantially lower than the CF calculated for the analogous periods in the recent years. As shown in Fig. 3a, this overall reduction reaches approximately −20% when compared to the average CF estimated for the months of March and April in the timeframe 2015–2019. In absolute values, this means an overall saving of GHGs in between ~5.6 and ~10.6 Mt CO_2e during the lockdown in Italy. Particularly high is the difference between the CF calculated for April 2020 (~26 Mt CO_2e) and the CF calculated for April 2019 (around 29% higher). Whereas the difference between the previous months of March 2020 vs. March 2019 is lower and aligned with the average (~18%). In contrast, the difference in CF estimated when comparing the pre-lockdown period with the same historical timeframe 2015–2019 is essentially negligible, being around +3% in January 2020 and −2% in February 2020 on average. In many cases, the GHG emissions estimated to have been released at the beginning

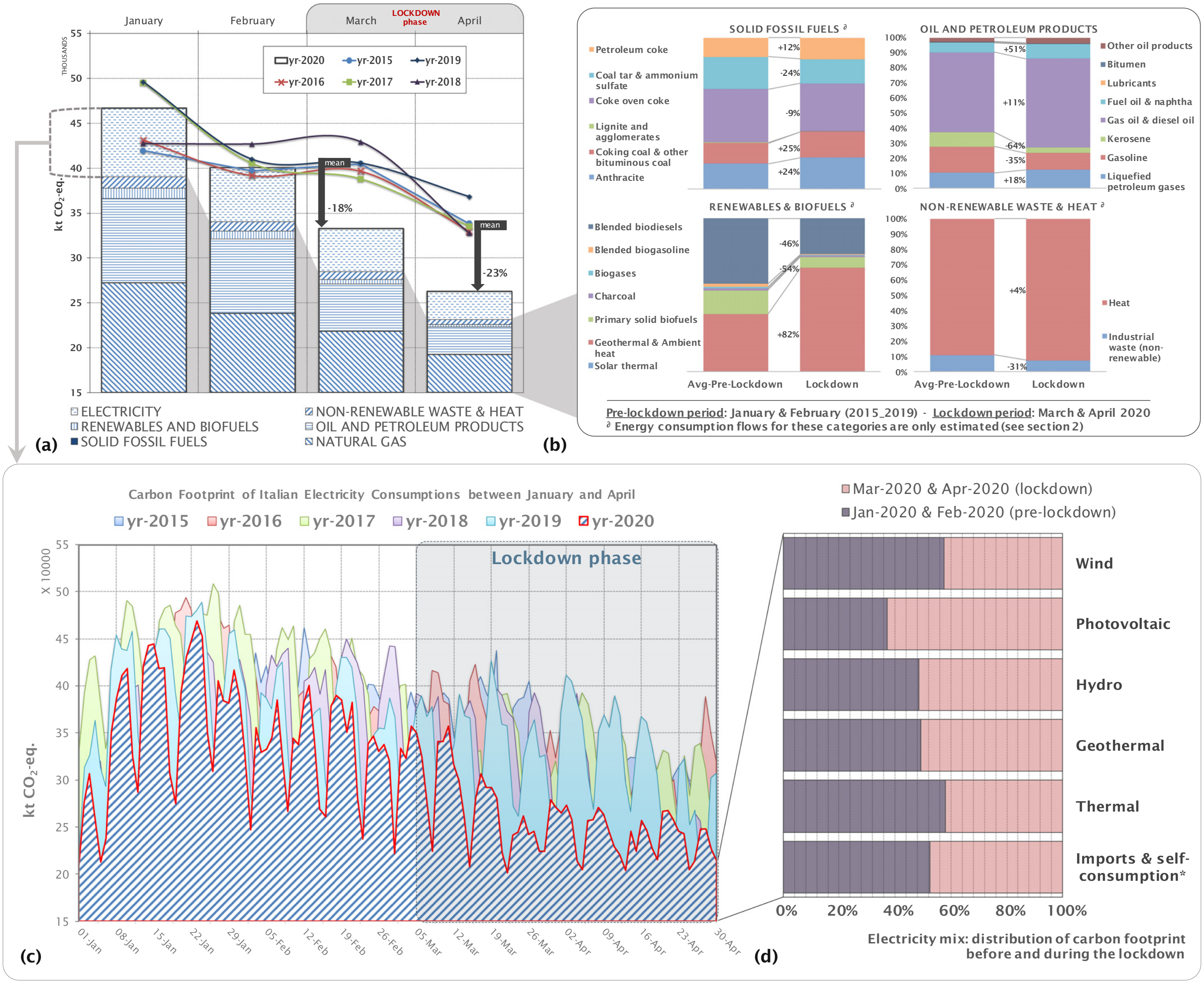

Fig. 3. (a) Comparison between the Italian CF trend associated with energy consumptions in the pre-lockdown and lockdown periods, which correspond respectively to January–February 2020 and March–April 2020, vs. the CF trends calculated from the previous years (from 2015 to 2019) and occurring in the same timeframes. For the year 2020 a disaggregation by six macro-categories of energy flows is provided, which is further detailed in (b) [variation in the relative contribution to the CF due to each consumed energy item in four energy flow categories, excluding electricity and natural gas], (c) [daily trend of CF associated with electricity consumptions], and (d) [variation in the relative contribution to the CF due to each components of the electricity mix, comparing pre-lockdown vs. lockdown periods; *the item “self-consumption” also includes the avoided GHGs associated with pumping-consumptions and the GHGs associated with operational infrastructure inputs].

of 2020 are higher than those estimated for the analogous period in previous years, up to an increase in the CF value of ~3.0 Mt CO_2e (in the case of January 2020 vs. January 2019). Fig. 3a also shows that three main categories of energy consumption flows mainly contribute to determining the CF, which are *natural gas* (by around 37% on average in 2020), *oil and petroleum products* (~30%) and *electricity* (~25%). The CF shares of the other energy categories are marginal, being around 5% represented by *non-renewable waste & heat*, 3% by *renewable and biofuels*, and less than 1% by *solid fossil fuels*. More details about the contribution of each sub-category energy flow are provided in Fig. 3b, while Fig. 3c and d depicts, respectively, the daily trend in CF due to the *electricity* consumptions and the relative contributions to this CF of each electricity mix component in the two phases of pre-lockdown and lockdown.

Fig. 3b in particular provides two types of information. On one hand, it shows the relative contribution of each subcategory of energy consumption flow to the total CF of its overarching category, both in the lockdown period and in the past (for this latter, considering again the average share from the timeframe 2015–2019). For example, the CF associated with the category of *solid fossil fuels* is dominated by the impact due to the consumption of coke (estimated to be around 32% in the lockdown period, but with less uncertainty around 35% in the pre-lockdown period). While the contribution of gas oil & diesel oil covers more than 50% of the CF of its *oil and petroleum products* category, followed by the subcategories of liquefied petroleum gas and gasoline (~10% and ~17%, respectively, in the pre-lockdown period).

On the other hand, the estimates of change in the share of contributions to the CF in each category (between the pre-lockdown and the lockdown period) suggest that, while in the categories of *solid fossil fuels*, *oil and petroleum products* and *non-renewable waste and heat* the overall distribution of the impact is kept quite constant over time (except for some exception; e.g. substantial reduction in the CF associated with gasoline and kerosene consumptions, by ~—35% and ~—64% on average, respectively), for the categories of *renewables and biofuels* some more relevant changes can be observed. For example, the CF associated with the use of primary solid fuels in this category decreases by around 54%, and with use of blended biogasoline and biodiesel by around 68%

and 46%, respectively, whereas the CF associated with the use of geothermal and heat pumps increases by more than 80% in the lockdown period.

In terms of GHG emissions reduction rates associated with *electricity* consumptions, Fig. 3c highlights on a higher temporal resolution scale (daily consumptions) that the distance from the average CF due to past *electricity* consumptions in the timeframe 2015–2019 was even higher in the lockdown phase than for the other categories of energy flows. For example, an average reduction by ~16% and ~23% in March and April, respectively, is observed compared to CF outputs from the last year 2019, with peaks up to −49% on specific weekends such as the 21st–22nd of March and the 4th–5th of April 2020.

Interestingly, Fig. 3d highlights that a substantial increase in the relatively contribution of the renewable sources of energy to the *electricity* generated CF occurs during the lockdown period (by around 23%), while the CF associated with the use of thermal electricity sources diminishes by around 28%. This suggests that, although the “renewable” component of the electricity mix is not “carbon free”, it has certainly contributed to considerably lowering the total value of CF due to *electricity* consumptions in the lockdown phase. More specifically, the CF associated with solar photovoltaics, electricity from geothermal energy sources, and hydropower increase respectively by ~68%, ~3% and ~6% in accordance with their consumption growths in the lockdown days of ~65%, ~1% and ~4% on average (as from the hourly energy balance datasets delivered by Terna, 2020; see Table S3-SM). While the consumptions of renewable energy carriers (among which the use of geothermal heat and ambient heat pumps, as indicated in Fig. 3b) have increased so highly in the lockdown phase, a general reduction in the use of fossil energy sources is observed which belongs to a significant decrease in the demand for combustion fuels (in particular with regard to fuels in the category of *oil and petroleum products*, the majority of which is imported and not domestically produced). Table S5-SM provides the monthly CF dataset for each energy consumption flow.

3.2. Spatial distribution of carbon footprint

When looking at the distribution of CF across the 107 provinces of Italy, it is worth noticing that there is a tendency towards higher impacts in the Northern regions, with very few exceptions in the central and Southern parts, including the islands. For example, in March and April 2019 (see Fig. 4a) a CF value higher than 2 Mt CO_2e (against an average CF by province of ~0.73 Mt CO_2e) is estimated for six Northern Italian provinces (in descending order from the highest: Milano, Modena, Torino, Brescia, Bergamo, Ferrara), and only for the province of Rome as an area outside the North. Therefore, to better understand the territorial heterogeneity of the lockdown effects on the CF impact, an estimation of the CF avoided by each province as compared to the 2019 CF values was performed, starting from the assumptions that the energy consumptions across regions and provinces follow the same patterns observed in previous years (see Section 2.2.3.1 for further details on the territorial allocation of the energy consumptions).

As shown in Fig. 4b, impact savings in absolute values mainly occur in the Northern provinces of Modena and Milano for avoided GHGs amounts of ~0.7 Mt CO_2e (Fig. 4b), followed by other provinces located in the regions of Lombardia (i.e. Bergamo and Brescia) and Emilia-Romagna (i.e. Ferrara). Not surprisingly, those are the Italian regions that, together with Piemonte (headed by high impact savings in the province of Torino) underwent the greatest effects of the pandemic (see further discussion below in Section 4.1). Similar territorial distribution patterns of GHG emissions and CF avoided are observed when data are shown per capita, as in Fig. 4c and d, respectively. In this case, however, slightly more homogenous scatters are outlined between the regions in the North of Italy (showing the highest CF values in 2019 but also the highest CF avoided during the lockdown) and the regions in central and Southern Italy, with a tendency towards lower values (meaning higher CF per capita) when moving to the South. This is because of the higher figures of resident population in those Northern provinces of Italy, which contribute reducing the discrepancies between the areas with high CF and with high impact avoided (i.e. when looking at the total impacts, only the Northern regions cover more than 60% of the total CF avoided, since almost 50% of the total Italian population resides there). Table S6-SM provides the entire dataset of CF results for each province and economic sector.

3.3. Estimations of post-lockdown carbon footprint trends

When looking at the total potential carbon footprint of Italy in the year 2020, an increasing trend of GHG emissions after the COVID-19 outbreak related lockdown measures is estimated as a likely consequence of the upturn in economic activities. As shown in Fig. 5a, such a growth in CF patterns is foreseen to occur with GHGs emission values in a range between ~434 and ~479 Mt CO_2e, which depends on the upper and lower reference scenarios calculated for three possible trends of GDP expected for 2020. Compared to the past 2017, 2018 and 2019 years, this means a potential reduction of the total yearly CF of, respectively, ~−7%, ~−6% and ~−9% when considering the “pessimistic” scenario (lowest bound in Fig. 5a, where the 2020 GDP is expected to decrease by 9.1% as compared to December 2019). Conversely, in the unlikely case that the GDP will grow following a BaU pace (upper bound, scenario 1 in Fig. 5a), the total CF might even overcome the historical impacts, namely by ~3% (vs. 2017), ~4% (vs. 2018) and ~0.03% (vs. 2019).

The probability and extent to which those predictions will concretely take place highly depend on the variability in upturns of each specific economic production and consumption component. Fig. 5b discloses the relative contribution of each economic activity sector to the CF estimated in the pre-lockdown phase. Essentially the transportation services within the tertiary sector, which contribute to around 25% of the total GHG emissions, and a few industrial sectors such as the machinery, iron & steel, non-ferrous metals & other, and non-metallic minerals productions, which together contribute to around 17% of the total GHG emissions, dominate with the housing sector (~29%) the CF estimated for the months of January and February 2020.

3.4. Carbon footprint intensity

The necessary information to disaggregate the lockdown-related CF into actual shares of economic sectorial CFs was still not available at the date this study was performed. Therefore, it can be assumed that the abovementioned key-contributing sectors have undergone substantial changes in March and April 2020, with a lesser focus given to the housing one (since this includes households consumptions related CF which are likely to be less dependent on the lockdown restrictions). These economic activities represent major sources for the reduction of CF observed in this period (i.e. most of the decrease in energy flow consumptions observed in the lockdown phase strongly relies on the use of fuels, which are mainly burnt in the transportation as well as by the metals and minerals industrial sectors). Should the productivity of these economic sectors share change over the next months until December 2020, this will certainly contribute to modify the predicted patterns of the total annual CF. The extent of these changes, however, are impossible to be foreseen at the present stage. An attempt to better understand the link between the upturn of economic productivity and the yearly CF is included in Fig. 6, which provides information on the possible variation of the CF intensity after the lockdown phase (estimated per euro of GDP in 2020). This depends on the three GDP related scenarios defined for this study, and suggests that the negative impact expected to occur on the GDP in 2020 will seemingly affect the national CF intensity. In particular, a slight reduction of GHGs per Euro of GDP is estimated when compared to 2019 patterns, i.e. in a range between −0.4% (scenario 3) and −1.3% (scenario 1, which is less likely to occur than scenarios 2 and 3). While a moderate increase in the CF

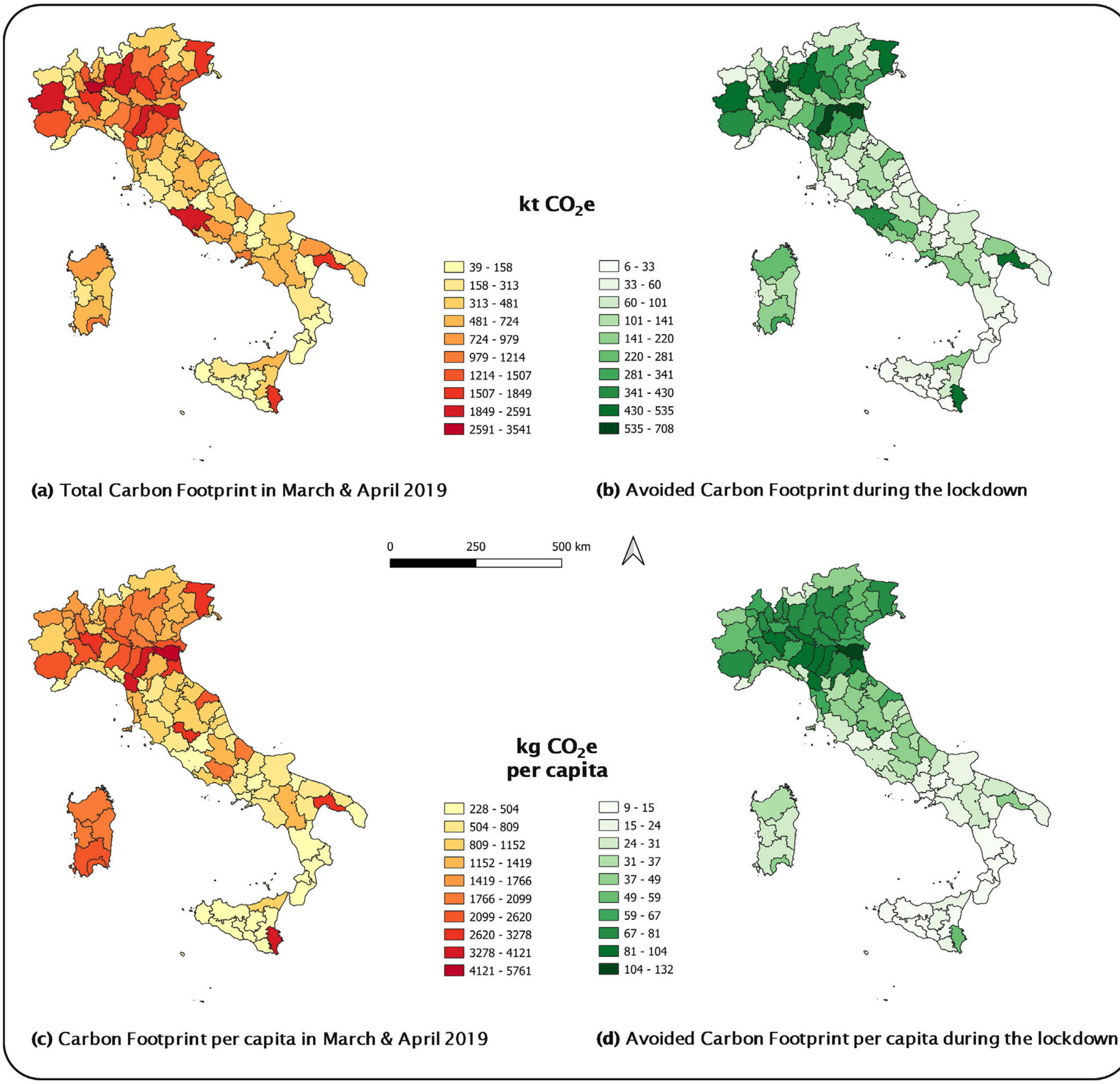

Fig. 4. Spatial distribution of carbon footprint (CF) impacts across 107 provincial areas in Italy: a) total CF calculated for March and April 2019, comparable with b) the CF impact saved in the same period during the lockdown phase; c) CF "per capita" calculated for March and April 2019, comparable with d) the CF impact saved in the same period during the lockdown phase (~March and April 2020).

intensity is expected when comparing the 2020 trends with values from the previous timeframe 2015–2018.

4. Discussion

4.1. Implications of the Italian lockdown on carbon footprint trends

Over the past few months, the COVID-19 pandemic has caused an unprecedented crisis with strong implications on the economic sectors worldwide. Italy has been one of the most affected countries in the world by COVID-19. The consequent lockdown undertaken by the Italian Government has had strong repercussions on the productivity of its energy sector, which is considered the major responsible for the national GHG emissions (~80% on annual basis; UNFCCC, 2020). This study has focused on evaluating how the energy sector in Italy, in particular with regard to the carbon footprint associated with the final consumptions of energy, has been affected by the imposed COVID-19 lockdown in terms of GHG emissions released in the atmosphere. The analysis has revealed that the ~9 weeks of lockdown in Italy have determined a significant reduction of the CF associated with the Italian energy consumptions when compared with pre-lockdown periods (Fig. 3). Results have shown that the CF has decreased by around 1/5 with respect to the CF values in the 2019's period of March & April which corresponds to the lockdown in 2020 (~−18 Mt CO_2e). When looking at the categories of energy consumption that mostly contributes to the CF, reductions compared to the 2019 correspond to ~−4% for *natural gas*, ~−41% for *oil and petroleum products* and ~−19% for *electricity*.

Findings from this work have however revealed that the relative contribution of each typology of energy consumption flow to the total CF has not significantly changed during the lockdown compared to previous trends. This is especially true concerning the categories of *solid fossil fuels*, *oil and petroleum products*, *non-renewable waste* and *heat*. However, the decrease of CF due to consumption of kerosene in the category of *oil and petroleum products* has been remarkable and in

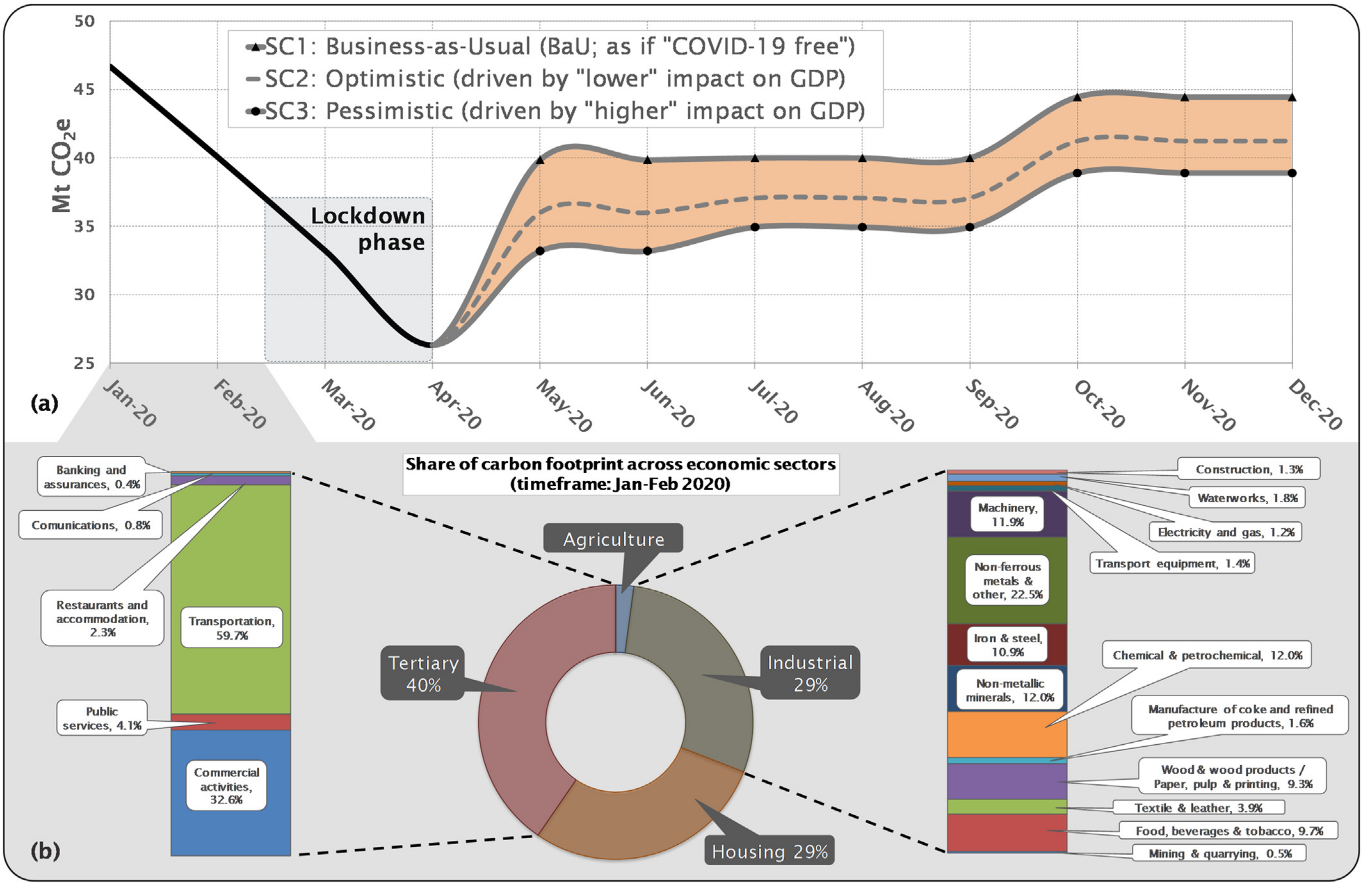

Fig. 5. (a) Estimated total carbon footprint (CF) progress in 2020, considering the trend in the pre-lockdown and lockdown phases, and projecting the CF over the post-lockdown period according to three possible scenarios of CF potentially occurring as a consequence of the variation in GDP (see Section 2.2.3.2 for further details); (b) disaggregation of the total CF by economic sectors relatively to the pre-lockdown phase.

agreement with the imminent crisis of the airline companies, which have been one of the hardest-hit industries in the early days of lockdown (Sobieralsky, 2020). Instead, in the *renewable and biofuels* category, our analysis has revealed a drastic increase of CF due to consumption of geothermal energy (which also includes the use of heat pumps) associated with a significant decrease of CF due to consumption of biodiesel and biofuels (Fig. 3), suggesting and confirming the likelihood that the mobility restrictions during the lockdown have played a key role to reduce the CF. It should be noted that for *heat* and *electricity* the lockdown has mostly entailed a shift of emissions from working places to households. In contrast, the transport sector has been essentially limited without any kind of shift to another transportation modality of the people. Transportation services during the lockdown have been limited to ensuring the supply of primary products and services (e.g. food, medical/sanitary care products, mails delivery, etc.), and therefore the GHG emissions associated with the transport sector have simply undergone a reduction.

This paper has also captured information about the spatial distribution of CF across the 107 Italian provinces, revealing that Northern regions were those with both the highest CF in the pre-lockdown, and the highest emission savings during the lockdown phases (Fig. 4). In particular, some provinces in Lombardia and Emilia Romagna have recorded the highest values of GHGs saving during the lockdown. This finding reflects the fact that Lombardia and Emilia Romagna historically represent the heart of the industrial productivity of Italy (Collevignarelli et al., 2020) characterized by a high level of pollution (Conticini et al.,

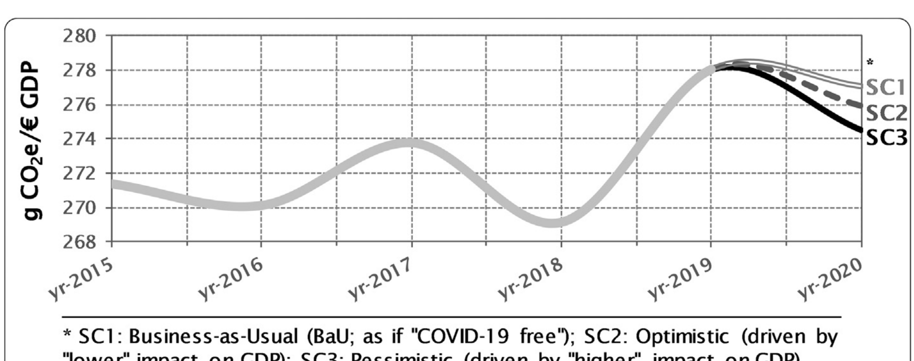

Fig. 6. Trend of carbon footprint (CF) intensity (CF per euro of Gross Domestic Product – GDP) calculated from January 2015 to December 2020. Curves for 2020 (post-lockdown) underpin three possible scenarios of CF potentially occurring as a consequence of the variation in GDP (see Section 2.2.3.2 for further details).

2020) also due to a specific geomorphology (Luisetto et al., 2020). Moreover, these regions have reported the first virus cases in Italy. As such, a large number of economic activities have been drastically reduced (if not completely shut down) from one day to another for several weeks, and the population has been confined for a slightly longer period than in other provinces of the central and Southern Italy. Similar patterns have been observed at the per capita level, where the North of Italy has recorded the highest values of both CF before and emission savings after the lockdown. Although the regions in the central and Southern Italy have recorded lower values of GHG emissions saved (both total and per capita), it is interesting to note how a Southern province, the Province of Taranto (Puglia region), shows CF values in line with those found in Northern Italy for both CF in 2019 and emissions saved over the lockdown. This is mainly due to the presence of a large steel manufacturing plant close to the urban area of Taranto, which operates since the sixties and it also been the subject of analyses investigating the exposure of local population to air pollution (Leogrande et al., 2019). Similar considerations about the link between the temporary closure of relevant economic activities, their spread in the national territory and the effects on CF can also be done for other areas, showing the sensitivity and effectiveness of the spatially-explicit model proposed here to trace CF impact distributions at the level of province.

This paper has also estimated the post-lockdown impact trends of the total CF according to three possible scenarios occurring because of the variation in GDP in Italy. This has been important to offer some preliminary insights on the relationship between economic (via GDP) and environmental (via CF) aspects in connection with the COVID-19 outbreak and the relative lockdown effects. Not surprisingly, the analysis suggests that the stronger economic crisis is, the more CF reduction occurs. Indeed, the BaU GDP-related scenario has corresponded to the worst-case scenario for CF and the pessimistic GDP-related scenario has corresponded to the best Italian CF performance. However, looking at the Italian CF intensity, this study has revealed that even in the pessimistic GDP-related scenario, Italian CF would record a higher value with respect to 2015, 2016, 2017 and 2018 levels. Instead, a slight reduction would be observed with respect to 2019 levels. This means that even the worst-case evolution in terms of GDP would not be sufficient to counterbalance the significant increase of Italian CF intensity occurred in 2019. In this context, the emergency of COVID-19 and the associated lockdown require us to reflect on the weakness of our system and the urgent need to rebuild a more robust, ethical and equitable social-ecological economy (Spash, 2020). Although this situation has caused an imminent global economic crisis, it should also represent an opportunity to rethink our future production and transport systems (Hepburn et al., 2020) and to make our society less vulnerable to future climate, ecological or public health risks (Burke et al., 2020). For instance, a general reconsideration of the transport sector (De Vos, 2020) is highly expected as well as an overall change in the supply chain strategy only based on economic driving forces. In general, it is expected that climate change may be treated with the same urgency as the COVID-19 pandemic (Herrero and Thornton, 2020).

4.2. Relationship between carbon footprint and the COVID-19 outbreak

The present study, to date, is the first one to assess the “proactive” effects of lockdowns in Italy (i.e. fourth major GHGs emitter after Germany, UK and France in 2017; EEA, 2020) due to COVID-19 on the environment, focusing on the carbon footprint. A recent paper has estimated a daily global CO_2 emissions decrease within the range of 11% and 25% by early April 2020 compared with the mean 2019 levels (Le Quèrè et al., 2020). Despite the methodological and scope differences, it should be noted that our findings are within the range estimated by Le Quèrè et al. (2020). However, with the data and information available to conduct this study, the retroactive effects such as direct cause-effect relationships between the spread of COVID-19 in Italy and the amount of GHGs released in the atmosphere could not be assessed, and they were left out of scope. Accordingly, several other variables not considered here can play a significant role and have a different weight in determining the probability of infection and its liaison with impacts on human health and ecosystems (Coccia, 2020; Sobral et al., 2020). Nevertheless, this study has revealed that the greatest impact savings in terms of CF have occurred across the Italian regions with the highest records of infections. This observation has been statistically confirmed by a high degree of correlation ($r = 0.60$ of Pearson's coefficient) obtained by relating the total CF avoided per province with the number of positive cases to COVID-19 in each province (Civil Protection Department, 2020). Since the longest and most constraining lockdown measures occurred in the Northern Italian regions of Lombardia, Piemonte and Emilia-Romagna, such a strong statistical correlation between the major infected areas and the highest GHG emissions saved confirms the effectiveness of the lockdown measures in reducing the CF of Italy.

On April 2020, the Mauna Loa Observatory has recorded a concentration of global CO_2 in the atmosphere equal to 416 ppm (NOAA, 2020), which is the highest value ever monitored. When looking at the results of the present study, such global observation might seem weird, because lockdowns have been implemented by most of the countries around the world. However, several reasons may explain this apparent contradiction. One of the most straightforward motivations is that CO_2 resides in the atmosphere for many years (IPCC, 2005). Therefore, the effect of a few months of lockdown on the global concentration of CO_2 in the atmosphere may be considered negligible. Unlike atmospheric pollutants, GHGs persist in atmosphere making not perceptible the lockdown effect by using direct measurements or satellite monitoring observations. Consequently, environmental accounting-based estimations such as the one presented in this paper represent the only available tool to anticipate the forthcoming impact of drastic changes in economic activities worldwide (caused e.g. by such lockdown measures) on GHG emissions and associated climate change. GHGs inventory analyses based on official statistics and environmental accounting databases may provide robust results and constitute a relevant framework for further advancements in the assessment of environmental impacts. Accordingly, the CF trends estimated and disclosed in this study may be regarded as proxy indicators to better understand the impact trends due to other pollutants that are typically released by the same sources of GHG emissions, such as $PM_{2.5}$, PM_{10}, NO_2 (Wu et al., 2020; Travaglio et al., 2020). Moreover, starting from the energy consumption flows inventoried here, additional investigations may be developed to assess the retroactive effects of COVID-19, thus also indirectly supporting the need for research on the role of environmental factors in transmission or lethality of COVID-19 (Qu et al., 2020). For example, further research may be conducted to understand the role and contribution of wooden biomass to the CF as well as other human health impact synergies. Since burning wood not only generates biogenic carbon emissions but also particulate matter, it is likely that exposure to biomass smoke might be associated with COVID-19 (Thakur et al., 2020). Therefore, the role of wood combustion as source of atmospheric particulates (and therefore as an environmental co-factor that have potentially contributed to the extremely high level of lethality occurring in Northern Italy; Conticini et al., 2020) might be put in the list of those challenges that deserve further, immediate, and in-depth experimental investigations (Sanità di Toppi et al., 2020). Because the consumption of natural gas for heating has not been substantially reduced during the lockdown (not surprisingly, due to the increase in housing activity), one could argue that the same occurred for the consumption of wooden biomass. A slight increase in biomass use for producing electricity (by around 2%) has been observed during the lockdown, and its contribution to the CF accounted for. However, no further evidence has been found in the literature to support the CF results of the present study concerning the role of wood combustion, since data about the consumption of renewable energy and biofuels was not yet available and could only be estimated.

4.3. Potential sources of uncertainty, model limitations and caveats

The CF results presented in this paper are not free of potential uncertainties, which are mainly associated with the quality of the data inventoried and the methodological assumptions undertaken to build the assessment model.

A first limitation concerns the data coverage. The inventory of energy consumptions has been based on the most recent, up to date and comprehensive datasets of open data sources accessible on the internet, which cover every specific economic sector of production and consumption at the "Section" activity level according to NACE Rev.2. Nevertheless, the use of some specific energy flows for which data was available until January 2020 (i.e. those belonging to the categories of solid fossil fuels and manufactured gases) or 2018 (without monthly distribution; i.e. those belonging to the categories of renewable energy and biofuels, non-renewable waste and heat) could only be estimated for the remaining periods, which necessarily introduced a main layer of uncertainty in the analysis. Despite this uncertainty has not been quantitatively characterized, it can be argued that its propagation within the assessment model is relatively low. When looking at the timeframe 2015–2018 (for which there is a robust and full coverage of data), the sum of the relative contributions of those energy consumption flows to the total CF is seemingly much lower (~7% of the yearly CF) than that provided by other categories of energy (notably natural gas, oil and petroleum products, and electricity; ~93%), for which instead an accurate and extensive dataset was available at least until March 2020 for natural gas, and April 2020 for electricity and oil and petroleum products. This certainly contributes to lowering the data related uncertainty and ensuring consistency in the overall CF output. Another uncertain aspect related to data pertains the consideration of the lockdown phase in the present model, which has been approximated to occur between 1st March and 30th April 2020. In reality, however, the lockdown period started at the end of February in certain areas and gradually over other regions until the first 10 days of March, when all Italy was covered. Similarly, the re-opening of economic activities was gradually permitted between 3rd and 24th of May. On top of the difficulty to model such a spatial and temporal variability, no data were available to account for the energy consumptions on a daily basis and until May, except that for electricity. This is the reason why a "monthly"-defined lockdown period covering March and April 2020 was assumed. Because electricity consumptions contribute by more than 25% to the CF during the lockdown, we can arguably infer that similar trends can be expected for the other energy consumption flows such as natural gas and oil and petroleum products. Table S7-SM provides the entire dataset of daily CF results for electricity, from 1st January 2015 until the 24th of May 2020. Not surprisingly, the CF trends do not substantially increase in the first half of May 2020, in compliance with the progressive re-opening of the economic activities. This suggests that a longer lockdown period could have been modelled in the present study. Taking the 30th April 2020 as the end of the lockdown period is nevertheless considered more reasonable and safe to keep consistency in the computation and increase the accuracy and representativeness of data.

A second layer of uncertainty can be attributed to i) the definition of three GDP-based scenarios implemented to predict the future trends of CF and their total amount for 2020, and ii) the methodological approach implemented to forecast the recovery of economic productivity between May and December 2020. In both cases, the uncertainty is associated with a set of arbitrary assumptions and calculation factors whose pertinence cannot be validated beforehand, but only when new data will be disclosed in the next future (Alamo et al., 2020). The projections shown in Figs. 5 and 6 are based on the hypothesis of a progressive (and quite linear) recovery of the economic productivity in the post-lockdown phase. This recovery has been modelled using incremental factors defined a priori that estimate an upturn of the GDP at the 2nd, 3rd and 4th quarter of 2020 (Section 2.2.3.2). A sensitivity analysis was therefore run using several combinations of those factors within the range of −25% (i.e. where GDP at 2nd quarter is 25% lower than GDP at 1st quarter) and +4.7% (i.e. full recovery of GDP already in June 2020), which both underpin unlikely GDP occurrences. The variability of CF within this wide range brings to a delta of around ~36 Mt CO_2e on average across the three scenarios, which represents around 8% of the total annual CF estimated in Fig. 5. Such a relatively low margin of error suggests that the approach of estimating CF trends as associated with GDP forecasts is a simplified practical solution to obtain realistic CF accounts. The constant trend of the CF to GDP ratio observed in the past timeframe (~0.3 kg CO_2e per Euro on a yearly basis; see Fig. 6), further supports this methodological rationale of using GDP as a proxy to estimate national CF profiles. Anyhow, the use of a less subjective and more sophisticated predictive modelling approach than the one adopted here could certainly reduce the uncertainty linked to the post-lockdown CF trends. In this regard, the application of data-driven estimation methods represent a valuable and effective alternative to ensure more consistency to the projections, as recently proposed, for example, to forecast the spread and fluctuations of COVID-19 infections (e.g., Tomar and Gupta, 2020). However, the scope of the present paper was centred on the CF assessment of the lockdown-related effects in comparison with historical trends, whereby the CF predictions made for the future months of 2020 only represent an informative add-on to the analysis, without claiming to become an absolute reference. Accordingly, such estimates must be regarded with care, and additional studies might be conducted in the future to build a specific prediction model, if needed for example to support decision-making process.

Results uncertainty may be eventually also associated with the use of CF factors applied to convert the consumption flows into CO_2-equivalents. However, these factors have been calculated using a life cycle assessment approach, which is common practice for the calculation of CF. Moreover, each calculation has built upon best-in class data from life cycle inventory processes representative of state-of-the-art average technologies, the majority of which have an ad hoc coverage for Italy. Therefore, this third layer of uncertainty is marginal to potentially impact on the reliability of results when compared to the uncertainty introduced within the model by the other two sources above.

Additional research must be conducted in the near future to confirm and complement the preliminary findings from this study. The GHGs inventory compiled in the present work is fairly representative and complete for what concerns the assessment of carbon footprint associated with energy flows across all sectors of consumption. Because energy flows represent the major driver of every life cycle activity producing goods and services for final consumptions, it is therefore possible to argue that the majority of GHGs embodied in the yearly country consumptions have been taken into account. Nevertheless, the analysis has not included the GHG emissions indirectly due to the life cycle activity of imported raw materials and manufactured products not belonging to the different energy flow categories (e.g. waste, livestock). All these direct and indirect GHG emissions, although expected to be marginally affected by the lockdown, should be accounted for in the future to complete the CF assessment offered in this paper. Finally yet importantly, the carbon accounting balance should also consider the impact avoided due to carbon removals from the atmosphere typically associated with activities of land use, land use change and forestry.

5. Conclusions

An unprecedented lockdown of social and economic activities due to the COVID-19 outbreak occurred in Italy for around two months, approximately between March and April 2020. Through a comprehensive accounting of GHG emissions associated with energy consumptions by every sector of the economy (industrial, agricultural, tertiary and housing) and province areas of Italy, this research study has estimated a relevant decrease in the carbon footprint burden by around 20% compared with 2015–2019 levels. This has been mainly due to a significant reduction in the consumption of natural gas, oil and petroleum products and electricity. Northern Italy has been the area with the highest emissions avoided during the lockdown even at the per capita level. A scenarios analysis based on three possible GDP prospects has further revealed that, even in the most pessimistic evolution of the GDP at the end of 2020, the reduction in CF impacts would not be sufficient to drive the Italian CF intensity values to levels lower than those assessed in the past timeframe 2015–2018.

A wide discussion nowadays concerns the Italian socio-economic "recovery" after the lockdown phase. Assessing the implications of COVID-19 related lockdown in terms of GHG emissions can provide crucial information about the potential repercussions of the Italian economy on climate change, giving important insights with regards to the potential opportunities to mitigate GHG emissions in the future. Despite these were certainly exceptional and drastic, the consequences of which for the economic upturn are still uncertain, such an experience has nevertheless opened up a new room for evaluating and eventually calibrating the deployment of more sustainable energy production and consumption models to achieve the Italian climate targets. Again, investments on renewable energies may be pondered to better understand the benefits of the effort required in terms of GHG mitigation. From this point of view, the outcomes illustrated here afford new knowledge upon which the implementation of sustainable finance, innovation and policy initiatives may be investigated to address climate change, which is still the biggest challenge of our times.

CRediT authorship contribution statement

Benedetto Rugani: Methodology, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Dario Caro:** Conceptualization, Resources, Writing - original draft, Writing - review & editing.

Declaration of competing interest

We have no conflict of interests for the paper titled: Impact of COVID-19 outbreak measures of lockdown on the Italian Carbon Footprint.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139806.

References

Acter, T., Uddin, N., Das, J., Akhter, A., Choudhury, T.R., Kim, S., 2020. Evolution of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) as coronavirus disease 2019 (COVID-19) pandemic: a global health emergency. Sci. Total Environ. 730, 138996.

Alamo, T., Reina, D.G., Mammarella, M., Abella, A., 2020. COVID-19: open-data resources for monitoring, modelling, and forecasting the epidemic. Electronics 9 (187), 827. https://doi.org/10.3390/electronics9050827.

Bao, R., Zhang, A., 2020. Does lockdown reduce air pollution? Evidence from 44 cities in Northern China. Sci. Total Environ. 731, 139052.

Brockwell, P.J., Davis, R.A., 2016. Introduction to Time Series and Forecasting. Third edition. Springer 978-3-319-29852-8 https://doi.org/10.1007/978-3-319-29854-2.

Burgio, E., Piscitelli, P., Lauro, R., Colao, A., 2020. The Italian war-like measures to fight coronavirus spreading: re-open closed hospitals now. EClinicalMedicine 21, 100320.

Burke, J., Fankhauser, S., Bowen, A., 2020. Pricing carbon during the economic recovery from the COVID-19 pandemic. Policy brief of Grantham Research Institute on Climate Change and the Environment (Centre for Climate Change Economics and Policy). Available here. The London School of Economics and Political Sciencehttp://www.lse.ac.uk/GranthamInstitute/publication/pricing-carbon-during-the-economic-recovery-from-the-covid-19-pandemic/.

CarbonBrief, 2020. Analysis: coronavirus temporarily reduced China's CO2 emissions by a quarter. Available at. https://www.carbonbrief.org/analysis-coronavirus-has-temporarily-reduced-chinas-co2-emissions-by-a-quarter.

Caro, D., 2018. Carbon footprint. Encyclopedia of Ecology , pp. 252–257 ISBN: 978-044464130-4. https://doi.org/10.1016/B978-0-12-409548-9.10752-3.

Caro, D., Rugani, B., Pulselli, F.M., Benetto, E., 2015. Implications of a consumer-based perspective for the estimation of GHG emissions. The illustrative case of Luxembourg. Sci. Total Environ. 508, 67–75.

Carugno, M., Consonni, D., Randi, G., Catelan, D., Grisotto, L., et al., 2020. Air pollution exposure, cause-specific deaths and hospitalizations in a highly polluted Italian region. Environ. Res. 147, 415–424.

Civil Protection Department, 2020. Civil Protection Department of the Presidency of the Council of Ministers. Data available at. https://github.com/pcm-dpc/COVID-19, Accessed date: 1 May 2020.

Coccia, M., 2020. Factors determining the diffusion of COVID-19 and suggested strategy to prevent future accelerated viral infectivity similar to COVID. Sci. Total Environ. 729, 138474.

Collevignarelli, C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., Miino, M.C., 2020. Lockdown for CoVID-2019 in Milan: what are the effects on air quality? Sci. Total Environ. 732, 139280.

Conticini, E., Frediani, B., Caro, D., 2020. Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy? Environ. Pollut. 261, 114465.

Contini, D., Costabile, F., 2020. Does air pollution influence COVID-19 outbreaks? Atmosphere 11, 377.

De Vos, Jonas, 2020. The effect of COVID-19 and subsequent social distancing on travel behavior. Transportation Research Interdisciplinary Perspectives 5 (100121). https://doi.org/10.1016/j.trip.2020.100121.

ecoinvent, 2020. The ecoinvent® v3.6 Database. The Swiss Centre for Life Cycle Inventories, Dübendorf (CH).

EEA, 2020. European Environment Agency: data viewer on greenhouse gas emissions and removals, sent by countries to UNFCCC and the EU Greenhouse Gas Monitoring Mechanism (EU Member States). Available at. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer, Accessed date: 25 May 2020.

ESA, 2020. European Space Agency. Video available at. https://www.youtube.com/watch?v=mZmFWcPeqGk, Accessed date: 25 May 2020.

Eurostat, 2020. Energy balances. Available at. https://ec.europa.eu/eurostat/web/energy/data/energy-balances, Accessed date: 25 May 2020.

Fattorini, D., Regoli, F., 2020. Role of the chronic air pollution levels in the Covid-19 outbreak risk in Italy. Environ. Pollut. 264, 114732.

GU, 2020. Gazzetta Ufficiale della Repubblica Italiana - Raccolta degli atti recanti misure urgenti in materia di contenimento e gestione dell'emergenza epidemiologica da COVID-19. Available in Italian language at. https://www.gazzettaufficiale.it/attiAssociati/1/?areaNode=12, Accessed date: 25 May 2020.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment - Theory and Practice. Springer International Publishing AG, Cham, Switzerland.

Helm, D., 2020. The environmental impact of the coronavirus. Environ. Resour. Econ. https://doi.org/10.1007/s10640-020-00426-z.

Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., Zenghelis, D., 2020. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? Forthcoming in the Oxford Review of Economic Policy. 36. Oxford Smith School of Enterprise and the Environment, p. S1 (Working Paper No. 20-02 ISSN 2732-4214)

Herrero, M., Thornton, P., 2020. What can COVID-19 teach us about responding to climate change? Lancet (Planet. Health) https://doi.org/10.1016/S2542-5196(20)30085-1.

Huang, C., Wang, Y., Li, X., Ren, L., Zhao, J., et al., 2020. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. Lancet 395, 497–506.

IMF, 2020. International Monetary Fund (2020). World economic outlook, April 2020: the great lockdown. World economic outlook reports. Available at. https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020, Accessed date: 25 May 2020.

IPCC, 2005. In: Metz, B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L.A. (Eds.), IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (442 pp).

IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guideline for National Greenhouse Gas Inventories. IGES, Japan.

IPCC, 2013. The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 8: Anthropogenic and Natural Radiative Forcing.

ISTAT, 2020a. I.Stat: warehouse of statistics produced by the Italian National Institute of Statistics (ISTAT). Available at. http://dati.istat.it/, Accessed date: 25 May 2020.

ISTAT, 2020b. Monthly report on Italian economy. Available online at. https://www.istat.it/en/archivio/242519, Accessed date: 25 May 2020.

Le Quèrè, C., Jackson, R.B., Jones, M.W., Smith, A.J., Abernety, S., et al., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. https://doi.org/10.1038/s41558-020-0797-x.

Leogrande, S., Alessandrini, E.A., Stafoggia, M., Morabito, A., Nocioni, A., et al., 2019. Industrial air pollution and mortality in the Taranto area, Southern Italy: a difference-in-differences approach. Environ. Int. 132, 105030.
Lu, R., Zhao, X., Li, J., Niu, P., Yang, B., et al., 2020. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 395 (10224), 565–574.
Lucchese, M., Pianta, M., 2020. The coming coronavirus crisis: what can we learn? Intereconomics 55, 98–104.
Luisetto, M., Almukthar, N., Mashori, G., Rafa, A.Y., Latyshev, O.Y., 2020. Pianura Padana geomorphology, climate condition and diffusion of COVID-19 hypotheses of work. J. Infect. Dis. Prev. Med. 8, 195. https://doi.org/10.35248/2329-8731.20.08.195.
Muhammad, S., Long, X., Salman, M., 2020. Covid-19 pandemic and environmental pollution: a blessing in disguise? Sci. Total Environ. 728, 138820.
NOAA, 2020. National Oceanic and Atmospheric Administration. Available at. https://www.esrl.noaa.gov/gmd/ccgg/trends/, Accessed date: 1 May 2020.
Ogen, Y., 2020. Assessing nitrogen dioxide levels as a contributing factor to coronavirus (Covid-19) fatality. Sci. Total Environ. 726, 138605.
PRé, 2020. SimaPro v9, LCA software.Available at. © PRé Consultants B.V.https://simapro.com/ Amersfoort, The Netherlands.
Qu, G., Li, X., Hu, L., Jiang, G., 2020. An imperative need for research on the role of environmental factors in transmission of novel coronavirus (COVID-19). Environ. Sci. Technol. 54, 3730–3732.
Sanità di Toppi, L., Sanità di Toppi, L., Bellini, E., 2020. Novel coronavirus: how atmospheric particulate affects our environment and health. Challenges 11 (1), 6.
Sciomer, S., Moscucci, F., Magrì, D., Badagliacca, R., Piccirillo, G., Agostoni, P., 2020. Sars-Cov-2 spread in Italy: what about the pollution role? Environ. Monit. Assess. 192, 325.
Setti, L., Passarini, F., De Gennaro, G., Perrone, M.G., Borelli, M., et al., 2020. Airborne transmission route of covid-19: why 2 meters/6 feet of inter-personal distance could not be enough. Int. J. Environ. Res. Public Health 17 (8), 2932.
Sobieralsky, J.B., 2020. Covid-19 and airline employment: insights from historical uncertainty shocks to the industry. Transp. Res. Interdiscip. Perspect. 5, 10012. https://doi.org/10.1016/j.trip.2020.100123.
Spash, C.L., 2020. 'The economy' as if people mattered: revisiting critiques of economic growth in a time of crisis. Globalizations https://doi.org/10.1080/14747731.2020.1761612.
Terna, 2020. Data on load, generation and transmission in Italy. Download Center of Terna Terna S.p.A. (Italian transmission system operator, responsible for electricity transmission and despatching). https://www.terna.it/en/electric-system/transparency-report/download-center, Accessed date: 25 May 2020.
Thakur, M., Boudewijns, E.A., Babu, G.R., van Schayck, O.C., 2020. Biomass use and COVID-19: a novel concern. Environ. Res. 109586.
Tomar, A., Gupta, N., 2020. Prediction for the spread of COVID-19 in India and effectiveness of preventive measures. Sci. Total Environ. 138762.
Travaglio, M., Yu, Y., Popovic, R., Leal, N.S., Martins, M., 2020. Links between air pollution and COVID-19 in England. medRxiv 2020. https://doi.org/10.1101/2020.04.16.20067405.
UNFCCC, 2020. GHG profiles – annex I. Available at. https://di.unfccc.int/ghg_profile_annex1, Accessed date: 25 May 2020.
WBG, 2020. The World Bank database, hosted by the World Bank Group. Available at. https://data.worldbank.org/, Accessed date: 25 May 2020.
WHO, 2020. WHO announces Covid-19 outbreak a pandemic. Available at. http://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-19/news/news/2020/3/who-announces-covid-19-outbreak-a-pandemic, Accessed date: 25 May 2020.
Wu, X., Nethery, R.C., Sabath, B.M., Braun, D., Dominici, F., 2020. Exposure to air pollution and COVID-19 mortality in the United States. medRxiv 2020 (2020.04.05.20054502).
Zambrano-Monserrate, M.A., Ruano, M.A., Sanchez-Alcalde, L., 2020. Indirect effects of COVID-19 on the environment. Sci. Total Environ. 728, 138813.
Zanin, G.M., Gentile, E., Parisi, A., Spasiano, D., 2020. A preliminary evaluation of the public risk perception related to the COVID-19 health emergency in Italy. Int. J. Environ. Res. Public Health 17 (9), 3024.
Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., et al., 2020. A novel coronavirus from patients with pneumonia in China, 2019. N. Engl. J. Med. 382, 727–733.